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THE ABSORPTIVITY OF ICE: A CRITICAL REVIEW

J. B. Lyons and R. E. Stoiber

Dartmouth College
Hanover, New Hampshire

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J. B. Lyons and R. E. Stoiber

Dartmouth College
Hanover, New Hampshire

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Abstract

The literature on ice absorptivity determination is critically evaluated in the light of new measurements made by the authors. Clear flawless ice has transmissivities close to those of distilled water, with the infrared absorption bands offset slightly toward higher wavelengths. Bubbly ice, the variety commonly encountered in nature, has absorptivities in the range of 100 times greater than those for flawless ice; this effect is largely due to scattering.

In the visible and near infrared range polycrystalline ice has transmissivities close to those for single ice crystals. The differential absorptivity reported by Plyler for the e and o -rays is shown to be non-existent.

Introduction

Of the solar radiation incident on snow or ice at the earth's surface some is reflected, some absorbed, and the remainder transmitted. Measurements of the absorptivity of ice are fundamental to an understanding of the heat economy of snow and ice areas, and of such processes as ice melting and ablation. The rather extensive literature, however, contains numerous contradictory data, and there has been little attempt to evaluate the experimental results in such compilations as those of Dorsey (1940) or Mantis (1951). The present paper reviews the absorptivity data for ice in the light of experimental measurements made by the writers, and points out those values which currently appear to be most reliable.

Several factors affect the accuracy of absorptivity measurements. Among the more important of these is the nature of the surfaces through which the light is directed. Light transmitted at normal incidence across an optically flat interface, such as an air-ice contact, loses some of its intensity because

of reflection.   The amount of reflected energy can theoretically be calculated from the Fresnel formula: $r = \left(\frac{n-1}{n+1}\right)^2$ where r is the percentage of reflected light, and n is the index of refraction.   For an air-ice or ice-air interface r = 1.77%; thus even under optimum conditions a maximum of 96.5% of the incident light should be transmitted through a thin ice sheet.   Transmissivity readings must be corrected to 100% if one wishes to determine a value for the transmissivity (or absorptivity) within the solid.

In point of fact, despite the most careful preparation, including a final polishing on silk, ice rarely shows its maximum transmissivity.   Lack of optical surface flatness, scattering caused by imperfections (particularly bubbles) or inclusions, etc. reduce the transmissivity readings far below the values that would be determined if the ice were absolutely flawless and plane.   As an illustration of the experimental pitfalls we may cite a determination in our laboratory, in which a polished ice surface was frosted by a breath of air; transmissivity of the sample dropped from 90 to 3 percent. Because of the factors cited, all of which result in scattering or absorption of the light, it is the general procedure in making ice transmissivity measurements to take the maximum in a series of readings as the value most closely representing that for clear flawless ice (cf. Bode, 1909).

Occasionally this leads to difficulties.   We have, for example, recorded transmissivities as high as 97% (against the theoretical maximum of 96.50%), and an entire set of Kalitin's (1932) readings are likewise impossibly high.   In both these cases the errors may be instrumental, or due to stray radiation. Kalitin's readings (op. cit.) were made spectrographically; it is doubtful that his photodensitometer had the requisite accuracy.   Our readings were made optically with a Welch photoelectric densichron detector.   The detector readings were reproducible within $\pm$ 1 1/2%, but in ice transmissivity work this

degree of precision is not satisfactory unless the sample is at least 20 cm. thick, and flawless - a set of requirements difficult to satisfy in laboratory-grown or natural ice. The effects of scattering are exemplified by some of Sauberer's (1938) early data, in which he found that the reflected plus penetrative radiation equalled 120% of the incident radiation.

One other method has been suggested by several authors to avoid the correction involving the calculation of reflectivity by the Fresnel equation. Transmissivities through successively thinner segments of the same block of ice may be used to calculate an absorptivity coefficient by the following formula: $\ln\left(\frac{I_2}{I_1}\right) = -k \triangle x$, where I_2 and I_1 are measured transmissivities (uncorrected) and $\triangle x$ is the difference in thickness. This equation assumes that the surface reflectivities are the same, though unknown, during each measurement. There are two reasons why the method is impractical. The new surface prepared for each measurement probably does not have the same flatness and polish. Furthermore, the differences in transmissivities are so slight that an extra ordinarily large crystal would have to be thinned down in order to make the ratio of the transmissivities larger than the uncertainty in the individual readings. Our experience using this method on crystals up to 10 cm. thick is that it gives data which are less reliable than the method which involves the Fresnel correction.

The Absorptivity of Flawless Ice

The absorptivity of "flawless" ice, like that of water, may vary depending on the source of the sample; it also will vary depending on its perfection and freedom from defects. In table 1 (below) we have listed some of our ice absorptivity measurements for clear ice along with the most commonly cited values from the literature; we have omitted data such as those of Bode (1909) and Kalitin (1932) which are clearly erratic. The ice absorptivity coefficients

have been calculated from the formula: $I = I_o e^{-kx}$

I = transmitted light intensity (corrected)

I_o = initial light intensity (corrected)

x = thickness in cm.

k = absorptivity coefficient (in cm^{-1})

Table 1

Absorption Coefficients for Clear Ice
(λ in millimicrons, k in cm^{-1})

Investigator	Lyons - Stoiber		Plyler (1924, 1925)				Sauberer (1950)		Sauberer (1950)		Kalitin (1935)	
Thickness (cm)	3.9 - 11.2		0.5				14-16		1			
			o-ray		e-ray							
	λ	k	λ	k	λ	k	λ	k	λ	k	λ	k
	400 to	.000x	750	.030	750	1.02	315	.0011	800	.030	332	.006
	800 to	.00x	790	.072	810	1.12	350	.0005	900	.094	346	.006
	806	.035	850	.030	850	1.02	400	.0004	1000	.315	366	.005
	904	..056	890	.060	920	1.16	450	.0005	1100	.163	392	.005
	988	.097	950	1.02	950	1.02	500	.0008	1200	1.514	416	.005
	1104	.061	1020	.072	1060	1.47	550	.0013	1300	1.661	438	.005
			1100	.050	1100	1.20	600	.0020			446	.005
			1200	1.06	1290	2.55	650	.0034				
							700	.006				
							750	.011				
							800	.018				

Our measurements on ice absorptivity were made on laboratory-grown samples up to 11.2 cm. in thickness. As a source for monochromatic radiation we have used both a Bausch and Lomb monochrometer, as well as various combinations of Bausch and Lomb half-wave transmission type filters with appropriate Wratten filters to absorb unwanted wavelengths. The Welch densichron recorder consisted of two interchangeable phototubes, one with maximum sensitivity at approximately 410 mu. and the other with maximum sensitivity at about 800 mu. We have not listed detailed readings in the range from 400 to 800 mu. because the very high transmissivity readings in this range coupled with the $\pm$ 1 1/2% uncertainty in the densichron readings means that we can be confident

only of the relative order of magnitude of the absorptivity coefficients.

The clearly erroneous values from Plyler (1924, 1925) have been listed principally because the preferentially high absorptivity coefficients for the e-ray determined by him are not yet generally discredited (cf. Dorsey, 1940, p. 490). Using polarized light we have measured transmissivities of both the e- and o-rays in flawless single crystals of ice throughout the entire spectral range from 400 to 800 mu. and at intervals up to 1100 mu. The crystals used for measurement were oriented with the c-axis at right angles to the incident light. In this range of wavelengths there is no measurable differential absorption nor does the absorptivity coefficient for either ray differ perceptibly from that of unpolarized light. Ellis and Vanderberg (1954) in a study of the absorption spectra of birefringent crystals have also found almost identical transmissivities of the o- and e-rays in ice. Their measurements which cover the spectral range from the visible through 2300 mu. indicate a maximum transmissivity difference of 6% in a few spectral positions, but general equality otherwise.

The fact that there is no differential absorptivity within the visible range may be convincingly demonstrated in the laboratory by holding an ice crystal in the path of plane-polarized monochromatic light, and rotating the crystal into positions to transmit the e- and then the o-rays. At 700 mu. there is no observable transmissivity difference in a crystal 4 cm. thick. If Plyler's absorptivity coefficients at 750 mu. were assumed to apply approximately at 700 mu. such a crystal should transmit 89% of the o-ray, but only 1% of the e-ray.

In order to assess the effects of grain boundaries we have determined absorptivity coefficients on a sample of clear polycrystalline ice composed of crystals of an average diameter of 0.1 centimeters. The block was 11.2 cm. thick, and was irradiated in a direction normal to the columns. The

absorptivity for this sample was not measurably different from that of single crystals of ice; the values approximate those of table 1, and for that reason are not listed here. These results are rather surprising in view of the well-known fact that polycrystalline ice is deeply etched by infrared or long-continued solar radiation (provided the ice surface is reasonably well drained). One can only conclude that the increased absorption caused by impurities, defects, and inclusions at grain boundaries is so slight as to be unmeasurable by our methods.

Of the values listed in table 1, it is our opinion that the absorption coefficients determined by Sauberer (1950) are of the right order of magnitude for clear flawless ice. His readings, carried out over a period of years with the best photoelectric equipment are probably better than the similarly careful measurements of Kalitin (1932, 1935). They also agree with infrared measurements of Dornbrand (1952) who investigated the absorption spectra of ice and water in the 700 to 1800 mu. range, and concluded that the coefficients for water and ice were closely similar. Dornbrand's measurements were carried out in glass cells, and an insufficient amount of data are available to permit computation of the absorptivity coefficients.

Several investigators (Bode, 1909; Bosschieter and Errera, 1937; Cassel, 1936; Dornbrand, 1952; McLennan et al, 1928; Plyler, 1924; Polli, 1950; and Sauberer, 1950) have compared absorption spectra of water and ice over different portions of the spectrum. The data of table 1 compared with those of water (cf. Dorsey, 1940) lend considerable support to the assumptions of some authors (e. g. Reuter, 1949; Dornbrand, 1952) that the absorptivity coefficients for both substances are essentially equal. The positions of the absorption peaks for ice over most of the spectrum appear to be slightly offset toward longer wavelengths, although Cassel (1936) has reported displacement toward the short wavelengths in the ultra-violet. In water, as the

temperature is decreased from 100° to 20°C the absorption bands shift toward longer wavelengths (Collins, 1925), in conformity with the relative shift in ice and water at 0°C.

In table 2 (below) we have listed best values for the absorption bands of water and ice as reported in the recent literature.

Table 2

Strong Absorption Bands in Ice and Water

(λ in millimicrons, k in cm^{-1})

Ice			Water		
λ	k	Investigator	λ	k	Investigator
166	-	Cassel, 1936	178	-	Cassel, 1936
-	-	-	760	.012	Curcio et al, 1951
1000 $\pm$	.315	Sauberer, 1950	970	.135	Curcio et al, 1951
1200 $\pm$	1.514	Sauberer, 1950	1190	1.03	Curcio et al, 1951
1400 $\pm$	23.0(?)	Bode, 1909	1440	29.5	Bocharov et al, 1958
2000 $\pm$	46.1(?)	Bode, 1909	1960	130.6	Bocharov et al, 1958
3050	-	Bosschieter et al, 1937	2940	6700	Bocharov et al, 1958

The fact that the absorption bands in ice are identified in approximately the same positions as those in water, plus the general agreement in the magni-tude of k values for these two materials (cf. also Sauberer, 1950) again indi-cates that for flawless ice the absorptivity coefficients are essentially identi-cal with those of clear distilled water.

The Absorptivity Coefficients of Bubbly Ice

Natural or artificial ice rarely is flawless, its commonest defects being air bubbles. Most of the laboratory and field measurements made on bubbly ice are based on transmissivity readings alone. It is generally not possible to calculate accurate absorptivity coefficients from such measurements be-cause the incorrect assumption must be made that the Fresnel formula can

be used to calculate the amount of reflected light. Sauberer (1938) appears to be the only investigator who has measured both transmissivity and reflectivity on the same sample, and his determinations are therefore probably the best of those listed in table 3 (below). Despite this, the agreement among the various investigators is surprisingly good, considering the variety of equipment and conditions represented by these experiments, and the variability in ice types investigated. One fact, obvious from the table, is the lack of data in the infrared range. The values reported by us in the last column of this table are average measurements for bubbly ice; transmissivities fluctuate widely in various protions of the samples depending on the number and shape of the air bubbles.

In the visible range, the only portion of the spectrum in which direct comparisons are possible, the absorptivity coefficients for bubbly ice are as much as two orders of magnitude greater than those of flawless ice. Much, if not all of this increased absorptivity represents light scattering due to reflection and refraction at the air-ice bubble interfaces.

Table 3

Absorptivity Coefficients for Bubbly Ice

(λ in millimicrons; k in cm^{-1})

Investigator	Kalitin (1935)		Polli (1950)		Sauberer (1938)		Sauberer (1938)		Pisiakova (1947)		Lyons-Stoiber	
Sample thickness cm.	10		8		2.5		4		32		2 - 4	
Description	Brown, bubbly pond ice		4 cm. bubbly* ice over 4 cm. clear ice		Clear ice with small air bubbles		Snow ice**		Bubbly lake ice		Artificial ice ***	
	λ	k	λ	k	λ	k	λ	k	λ	k	λ	k
	332	.048	white	.015	380	.040	380	.052	sunlight	.031	550	.047
	346	.049	violet	.046	435	.030	435	.038			589	.178
	366	.049	azure	.023	525	.029	525	.021				
	392	.048	green	.015	590	.031	590	.038				
	416	.042	clear red	.037	630	.023	630	.028				
	438	.044	dark red	.049	700	.023	660	.021				
	446	.048			735	.023	700	.031				
					760	.029	735	.038				
							760	.038				
							810	.061				

*Bubbles are 2-6 mm. diameter. Filters used to give light of colors shown.

**Reflected light for this sample was 45% to 49%.

***First sample represents 2% bubbles; second sample 4% bubbles. Average diameter of bubbles 0.36 mm.

A block of flawless ice 10 cm. thick would absorb only 2% of the 600 mu. radiation transmitted through it; a 10 cm. block of bubbly ice would, on the other hand, absorb about 26% of the same wavelength radiation. Stated another way, it would require a thickness of 347 cm. of clear ice to reduce this incident radiation to 50% of its initial intensity; 18 1/2 cm. of bubbly ice would accomplish the same result. These values which have been calculated from the Sauberer data of tables 1 and 2, are representative of those which hold

throughout the visible spectrum. Lack of data prevents similar comparison in the infrared, but there can be no question that the bubbly ice will be far more strongly absorptive because of its high scattering power.

Discussion

The great dependence of ice transmissivities on scattering by bubbles and imperfections indicates the impossibility of deriving a mean set of absorptivity coefficients for "average" lake ice, "average" glacial ice, or "average" sea ice. From the data in table 3, however, it seems likely that much fresh-water ice will have absorptivity coefficients in the range of .02 to .06 cm.$^{-1}$ over the visible spectral range (400 - 750 mu.) In the infrared there will be far stronger absorption, with coefficients considerably higher than .315 to 6700 cm.$^{-1}$ range indicated by table 2.

Melting of ice by solar radiation is largely due to infrared effects. The spectral distribution of solar energy reaching the earth's surface depends on atmospheric conditions, particularly the water vapor content. Generally, however, 50% of the incoming spectral energy lies between 350 and 700 mu.; 25% between 700 and 1200 mu; and 25% between 1200 and 4000 mu. (Haltiner and Martin, 1957, p. 75). If we consider the disposition of each langley of solar energy (1 langley = 1 cal/cm^2) which strikes on ice surface, we may calculate its absorption in the various wavelength bands. We shall consider separately the two ice types for which absorptivity coefficients have been determined - i.e. the flawless and the bubbly varieties. In table 4 (below) we have calculated average amounts of radiation absorbed by a 10 cm. thickness of these two varieties, assuming that the albedo of the clear ice is 2% (this would be true for solar angles of 60° or higher and an optically flat surface), and that the albedo for bubbly ice is 60% - a figure not far from averages reported in the literature for old coarse glacial ice. We have also

assumed average absorptivity coefficients from the data of tables 1 and 3.

Table 4

Absorption of Solar Radiation by Clear and Bubbly Ice of 10 cm. Thickness (in langleys)

Clear (2% albedo)			Bubbly (60% albedo)		
λ (in mu.)	Av. k(cm^{-1})	Langleys absorbed	λ (in mu.)	Av. k(cm^{-1})	Langleys absorbed
450 - 700	.002	.0098	450 - 700	.028	.048
700 - 1200	.020	.0435	700 - 1200	.10(?)	.063
1200 - 4000	50(?)	.2450	1200 - 4000	100(?)	.100

These numerical values are, of course, somewhat inaccurate for a variety of self-evident reasons, the postulated conditions for clear ice being particularly improbable. Nevertheless, there can be no doubt that 75% to 95% of the radiational melting effects are produced by absorption and scattering in the range above 750 mu. The interaction of these radiational effects with the other heat transfer processes occurring in snow and ice bear complex inter-relationships to one another which have been dealt with extensively in the recent literature.

Acknowledgments

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